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Exploding Wire Research 1774-1963

J. R. McGRATH

Energy Conversion Branch
Electronics Division

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U.S. NAVAL RESEARCH LABORATORY
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ABSTRACT

A review of Exploding Wire Phenomena (EWP) research is presented. This review covers the work performed from 1774 to the most current publication. Representative and significant studies are cited to indicate the difficulties associated with EWP research and the recent progress made in overcoming them.

PROBLEM STATUS

This is an interim report; work on this problem is continuing.

AUTHORIZATION

NRL Problem E02-02

The purpose of this report is to examine in some detail the more recent Exploding Wire Phenomena (EWP) literature. To introduce the subject, a review of selected EWP studies is presented to show the growing mastery of diagnostic techniques of this rather complicated phenomenon.

The content of the paper is divided into four principal sections chronologically, reflecting the periods of significant work and the introduction of new investigative techniques. The first period might be described as reportorial insofar as it served to describe generally the experiments of early workers and to stimulate further interest in this area. This period extends from 1774 to 1900. The second period extends from 1900 to 1941 and might be aptly described as developmental insofar as many varied techniques were applied to EWP research in an effort to understand its mechanism. The third period, from 1945 to 1959, might be described as diagnostic since instrumentation grew to be enormously more adaptable to observing high speed events. On this basis, theories are advanced to explain EWP. The fourth period might be reasonably described as one of applications, for a sufficient mastery and understanding had been achieved to allow for this. In this way, the subject is developed in chronological order and citations at the end of the paper are given according to the year in which they were formally published.

Of historical interest, the first published study of EWP was the work of Nairne[1] who connected rather long fine pieces of silver and copper to a Leyden jar which was then discharged. The result of the discharge caused the wire to thrash about inflicting minor injury to the experimenter. Singer and Crosse[2] reported sometime later on the work of M. DeNells in the Netherlands with interest in the explosive force. A method of depositing a very thin gold film by means of EWP was reported by Faraday[3]. The earliest photographs, both photographs and smoke plate recordings, were taken by v. Hubl and v. Obermayer[4]. Vapor deposits on glass were studied by Toepler[5] by exploding wires 2 to 3 mm away from the surface. These five authors represented the total published effort in exploding wire research from 1774 to 1900.

Early in the twentieth century, studies by Braun[6] showed that, following an explosion of the wire, the vapor then condensed on a glass plate was the metal itself and not an oxide. Nipher[7] showed that the passage of "negative Corpuscles" had a greater explosive effect.

The first really extensive spectrographic work was performed around 1920 by Anderson[8,9,10,11]. measured the spectral energy and found that the continuous spectrum is the same for the different metals tested. He pointed out that the absorption spectrum is more complete than

any other laboratory source, that the brightness is greater than the sun, and that the continuous background extends into the extreme ultraviolet region. Later, rotating mirror camera and spectrograph was employed to study EWP by Anderson and Smith[12], which was the topic of Smith's doctoral thesis[13]. Wendt and Ireon[14] exploded tungsten wires producing a gas which gave a helium spectrum and postulated transmutation. Smith[15] and Briscoe et al[16] repeated the experiment without evidence of the formation of helium. At about the same time as Anderson and Smith's work, similar photographic techniques were developed and higher quality spectroscopic data were taken in Japan. Hori[17] performed a study of absorption spectra of exploding wires. In a paper published much later after studies, Futagami[18] described the electrical and optical equipment. Nagaoka and Futagami[19,20,21,22,23,24,25] published several papers about 1927 reporting the data taken but did not offer a mechanism for EWP. They also exploded wires in a magnetic field[26]. Eckstein and Freeman[27] attempted to solve some of the problems of EWP by studying the spectra of lithium. Vaudet and Servant[28,29] studied the spectra of exploded wires in the Far Ultraviolet and Schumann Regions. Conn[30] from his studies concluded that the light produced was not reflected nor scattered and was not polarized for that reason.

A mechanism for EWP was suggested by Kleen[31] who made a detailed study of EWP using electrical capacity as the principal variable and rotating mirror photography as the recording detector. He suggested that the occurrence of vapor stria was initiated by prior formation of unduloids in the liquid phase. The mechanism of EWP was further studied by Wrana[32,33,34] in three papers which treated the interruption of the heavy surge current. He believed the interruption is due to a decreasing conductivity of the metal vapor near the boiling point. He classified the action according to the energy of the pulse.

World War II witnessed the accelerated development of the technical progress of leading scientific countries and the wholesale introduction of devices and techniques. In the fore of this situation was the measurement of time and the development of sensitive detection and recording equipment. With this in mind, the work in EWP progressed with surer footing.

Notable applications, specifically in high speed photography, were made including the development of high speed shutters such as the Rapatronic[35] and Faraday[36] shutters. Other improvements were made in the high speed framing camera[37,38]. Kerr-Cell photography was introduced for the first time in 1947[39]. The development of Kerr-Cell photography was pursued by Pugh et al[40], Heine-Geldern[41], and Zarem et al[42].

Muller[43,44], by means of a double Kerr-Cell camera, studied the shock waves in and around an exploding wire showing the shock wave system, the formation of dwell, and reignition. Tucker[45] and Webb[46] also took advantage of Kerr-Cell photography in their studies of EWP.

Spectroscopic investigations during this time period decreased. However, Rosen[47] investigated the spectra of diatomic oxides using EWP, and Hauver[48] used a rotating mirror camera as a spectrograph to study the changes in the spectrum with time.

Several cameras were developed to record high speed phenomena. The streak or rotating mirror camera was used by Bennett[49,50,51,52,53] as the principal instrument for investigating EWP. As a result of these studies, he concluded that an exploding wire acts as a transducer and consequently the circuit resistance depends on the density of the enclosing medium. He also studied the shock waves associated with EWP, relating the shock wave, electrical and heat energy. He further calculated the power lost in the circuit and produced shock fronts that propagated at speeds to Mach 9. Nadig et al[54] discussed the use of a high speed framing camera for studying EWP as did Zernon et al[55] who achieved framing rates of 10^6 per second. Korneff[56,57] studied current dwell by this means also.

In Russia, shadow photography, oscillographs and photometry were used by Kvartskhava et al[58] to study EWP. They suggested that the current flow is interrupted by shock waves, that melting occurred in bead-like dimensions and that evaporation began between the beads.

An effort was made by Lochte-Holtgreven[59] to classify EWP according to the order of the events: change of phase, non-conduction period or current-dwell, restrike, and oscillatory discharge. He suggested that superheating and shockwaves were essential features in EWP. Anderson and Neilson[60] advanced the action integral as having greater utility than the energy integral in EWP studies.

Day[61] used a method of photographic photometry which yielded spectral energy composition curves and brightness temperatures. Temperature estimates form line widths by Beuchelt and Bohm[62]. A four-color spectrograph, under photoelectric cell surveyance, provided Mayfield[63] with an estimate of temperature based on the Wien radiation equation. Prayning[64] defined temperature as the kinetic energy of the molecules.

Measurement and instrumentation techniques were continuously improved during this time period. The work of Kvartskhava et al[65] determined that in an EWP, the material is ejected at velocities up to 10^6 cm-sec and they suggested that this material ejection occurred in radial jets. They confirmed this[66] later in an experiment using bent wires. Measurement of radii vs. time and spectral luminosity vs. time was performed by O'Rourke et al[67] using a filmstrip camera. Tucker and Neilson[68] stored energy in a long coaxial cable and discharged it in 3 microseconds. They found that the energy-to-burst was dependent upon the current density. The current and voltage was easily measured because of the completely coaxial arrangement. Webb et al[69] studied the electrical and optical properties of very small diameter wires of Al, Cu, Ag, Au, Ni, and W using a very fast 2000 μμf system employing both a triggered gap and thyratron control.

Conn[70], Holtzworth and Hinz[71], and Liddiard and Drosd[72] studied the possible use of exploding wires as light sources. Liddiard and Drosd investigated their use for photography, recommending tungsten as best suited for this purpose. Holzworth and Hinz devised a practical system for using EWP as a light source. Patterson et al[73] investigated the feasibility of using an exploding wire as a spectrographic source for the analysis of some elements. Herzog[74] used EWP to produce shock, temperature and particle effects on several elements and an alloy. McFarlane[75] and Cnare[76] suggested the use of an EW as capacitor fuses. Marcus[77] found that EW was a desirable light source for certain photochemical reactions.

By 1960, due to the achievement of microsecond photography, Bennett[78] summarized the case for exploding wires. He stated that the early stages of heating were the same for all wires but that, depending upon the variables, two types of explosions have been detected: a continuous current type and a nonconducting type. While some events associated with both types are well recorded, an incomplete understanding remains about the behavior of the metal under these circumstances.

A comprehensive treatment of the work performed at NRL was reported by Langworthy et al[79], in which the design,construction and operation of three capacitor banks, including the associated electronic and optical equipment and techniques, was discussed. An elementary theory was presented.

The use of EWP has been generally studied by Ripoche[80] while Stevenson et al[81] has studied the spectral characteristics of exploding wires for excitation of optical masers.

Research[82] seemed to indicate a rôle for EWP as high intensity light sources for comm unications, propulsion units for space applications, and hypervelocity particle impact research.

Stambler[83] in a popular article stated the EWP has attractive possibilities for use as fuse initiators, explosive forming systems, and as fuses. EWP has been used to join otherwise difficult materials (quartz-to-quartz). Further use might be developed in shock research and studies of properties behind shock waves.

Miscellaneous applications included the study by Jones[84] using EWP to generate high power radio-frequency pulses which utilize the "current dwell" period. Karioris and Fish[85] employed EWP from metal wires in which the production of metallic aerosols of noble metals has been accomplished.

Measurement techniques had become sufficiently developed by this time that correlated electrical and optical measurements of exploding wires were then commonplace. Work by Bennett et al[86] involving a high-resolution streak camera and improved techniques resulted in time-correlated photographic records and electrical measurements. A voltage measuring system and its details were reported by Bey et al[87]. Kinetic electron temperature was calculated in the order of 2.6 Kev from photographic studies. Fournet[88] reported temperatures in the order of 2,000,000°K in his studies. Levine et al[89] made a study of the relation between resistance and energy to time. Webb et al[90] studied the effect of depositing large amounts of energy in a wire (10ev/ atom) before transplosion wherein pinch pressures were of the order of 10^3 atmospheres. The reproducibility of EWP has been established by Chace et al[91]. Tucker[92] used a square-wave generator to eliminate external circuit effects allowing a more exact interpretation of results. Reeves[93] measured the peak brightness temperature and spectral energy distribution of a spark discharge. Temperatures found ranged from 54000 to 68000°K by spectroscopic means.

Recently a significant amount of work has been done using photographic techniques. Bartels et al[94], using high speed photographs and spectrograms, showed that wires could be exploded only under special circumstances and that, in rare gas atmospheres of 100mm and 200mm the gas surrounding the wire broke down first. Bennett and Shear[95] observed that the shock wave comes not only from the unconfined expansion of the plasma of the peripheral arc. They developed a comprehensive picture of exploding wire by relating current, voltage, light and

streak photographs. An interesting photographic study was performed by Cnare[96] in which aluminum tubes were electrically exploded by introduction of 141 Kj of energy at 20 KV. It was shown by means of X-ray and framing camera observations that the tube collapses, melts and finally explodes. Streak camera, framing camera, and neutron detector were used by Katzenstein[97] to study the pinch effect on material of different atomic number. Evidence of pinch has been observed with materials of low atomic number by neutron and photographic means. Tucker[98] used Kerr-Cell photographs to obtain evidence of arcing around the wire at high current densities.

Chace[99] introduced the notion of classifying wire explosions as melting, slow, fast, and ablative. Keilhacker[100], based upon measurements, proposed the idea that the copper wire superheats and this process is interrupted by an inward progressing rarefraction wave. Nash and McMillan[101], based upon Bardeen's theory of metallic resistance, advanced a theory for "dwell" (i.e., current pause) wherein the temperature and "compression" changes were made to account for the resistance increase found by the authors. The increase in the wire resistance stops the first current surge and the time period during which the vapor density of the expanding material decreases enough to allow reignition of the discharge. Further, based on the spark breakdown mechanism, a hydrodynamic model was proposed to explain restrike from the "dwell" situation. Protopopov and Kul'garchuk[102] suggested that the metal vaporized from the surface inward by a rarefraction wave and, therefore, the speed of sound in the metal is an important property. Cnare[103] studied the striation of electrically exploded copper foils and suggested that striation instability was initiated as portions of the foil pass through a discontinuity (conductivity) at a phase transition. The resulting instability was viewed as a cause for uneven heating of the foil. Based upon this, it was suggested that the explanation of striation phenomena may also be applied to exploding wires in general. Webb et al[104] investigated wire explosions and suggested two models which might explain the behavior of the wires. The metals were divided into two classes: Class I represents materials with low boiling points and heats of vaporization. The experimental work of Bennett[105] revealed, from single fringe interferograms of exploding copper wires that the fluid disturbance may be divided into three regions: a compression, an annular plasma, and an expanding wire vapor. He indicated that electron temperatures as high as 200 eV may occur and that the arc boundary is probably a shock wave of the electron-driven type.

In summary, the purpose of this report has been to outline the general development of EWP up to 1963. While the scope of this paper

does not permit the inclusion of every investigator's work, an attempt to present representative papers has been made. The progress of EWP research has been described in terms of time periods. For a more complete list of studies performed, the reader is referred to the following excellent bibliographies by: Conn[106], Chace and Watson[107], and Abbott[108].

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